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Measurements of the CKM angle β in charmless loop-dominated B meson decays at BABAR

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Abstract

We report on preliminary measurements of time-dependent CP-violation asymmetries in charmless neutral B meson decays to $K^+K^-K^0$ (including resonant decays ϕK^0 and $f_0(980)K^0$), $\eta' K^0$, $\pi^0 K^0_S$, $K^0_S K^0_S K^0_S$, $K^0_S K^0_S$, $\rho^0 K^0_S$, ωK^0_S. The results are obtained from a data sample of up to 347 million $B\overline{B}$ pairs produced by e^+e^- annihilation at the $\Upsilon(4S)$ resonance collected with the *BABAR* detector at the PEP-II asymmetric-energy B-meson Factory at SLAC.

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1 Introduction

Measurements of time-dependent *CP* asymmetries in B^0 meson decays through a dominant Cabibbo-Kobayashi-Maskawa (CKM) favored $b \to c\bar{c}s$ amplitude [1] have provided a crucial test of the mechanism of *CP* violation in the Standard Model (SM) [2]. For such decays the interference between this amplitude and $B^0\overline{B}^0$ mixing is dominated by the single phase $\beta = \arg\left(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right)$ of the CKM mixing matrix. The *BABAR* measurement of β for these modes is $\sin 2\beta = 0.710 \pm 0.039$ [3].

In the SM, decays of B^0 mesons to charmless hadronic final states, such as ϕK^0, $f_0(980)K^0$, $K^+K^-K^0$, $\eta' K^0$, $\pi^0 K^0_S$, $K^0_S K^0_S K^0_S$, $\rho^0 K^0_S$, ωK^0_S, proceed mostly via a single loop (penguin) amplitude with the same weak phase as the $b \to c\bar{c}s$ transition [4]. In these modes, assuming the penguin dominance of $b \to s$ transition and neglecting CKM-suppressed amplitudes, the time-dependent *CP*-violation parameter S (defined in Eq. 1 below) is expected to be $\sin 2\beta$. However, CKM-suppressed amplitudes and the color-suppressed tree-level diagram, present in not pure-penguin modes (like $f_0(980)K^0$, $K^+K^-K^0$, $\eta' K^0$, $\pi^0 K^0_S$, $\rho^0 K^0_S$, ωK^0_S), introduce additional weak phases whose contribution may not be negligible [5, 6, 7, 8]. As a consequence, only an effective $S = \sin 2\beta_{\rm eff}$ is determined. The deviation $\Delta S = S - \sin 2\beta$ has been estimated in several theoretical approaches: QCD factorization (QCDF) [7, 9], QCDF with modeled rescattering [10], Soft Collinear Effective Theory (SCET) [11], and SU(3) symmetry [5, 6, 12]. The estimates are channel-dependent. QCDF and SCET models estimate ΔS to be positive in the most of modes. SU(3) symmetry provides unsigned bounds of the order $|\Delta S| \lesssim 0.05$ in the best case.

Due to the large virtual mass scales occurring in the penguin loops, the possible presence of additional diagrams with new heavy particles in the loop and new *CP*-violating phases may contribute to the decay amplitudes. In this case the measurements of significantly larger ΔS are a sensitive probe for physics beyond the SM [8]. Due to the different non-perturbative strong-interaction properties of the various penguin decays, the effect of New Physics (NP) is expected to be channel-dependent.

In the SM, the decay $B^0 \to K^0_S K^0_S$ is expected to be dominated by the penguin $b \to d$ transition, and is potentially sensitive to the presence of NP in a way analogous to $b \to s$ decays [13]. Neglecting CKM-suppressed amplitudes, the time-dependent *CP*-violating asymmetry parameters in this mode are expected to vanish (i.e. $S = 0$), while contributions from lighter quarks or supersymmetric particles could induce observable asymmetries [14].

In this summary we report preliminary measurements of *CP*-violating asymmetries in all of the above mentioned loop-dominated decays. The data sample used consists of 347 million $B\overline{B}$ pairs (227 million for $\rho^0 K^0_S$), recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). The data were collected with the *BABAR* detector [15] at the PEP-II asymmetric-energy e^+e^- collider. Detailed description for each analysis presented here are given in Refs. [16] and [17]. In Ref. [15] we describe the silicon vertex tracker (SVT) and drift chamber used for track and vertex reconstruction, the Cherenkov detector (DIRC), the electromagnetic calorimeter (EMC), and the instrumented flux return (IFR).

We reconstruct a B^0 decaying into the *CP* eigenstates $K^+K^-K^0$, $\eta' K^0$, $\pi^0 K^0_S$, $K^0_S K^0_S K^0_S$, $K^0_S K^0_S$, $\rho^0 K^0_S$, ωK^0_S (B_{CP}). From the remaining particles in the event we also reconstruct the decay vertex of the other B meson ($B_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{CP} - t_{\rm tag}$ of the proper decay times t_{CP} and $t_{\rm tag}$ of the *CP* and tag B mesons, respectively, is obtained from the measured distance between the B_{CP} and $B_{\rm tag}$ decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- system. Due to the K^0_S lifetime, the Δt for the modes $\pi^0 K^0_S$, $K^0_S K^0_S K^0_S$, $K^0_S K^0_S$ is obtained reliably by exploiting the knowledge of the average interaction point and from a global constrained fit to the entire $\Upsilon(4S) \to B^0\overline{B}^0$ decay tree, including the constraint from the lifetime of the B^0 meson.

The Δt distribution is given by:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \mp \Delta w \pm (1-2w)(-\eta_f S \sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t))], \quad (1)$$

where η_f is the *CP* eigenvalue of the final state f, the upper (lower) sign denotes a decay accompanied by a B^0 ($\overline{B}^0$) tag, τ is the mean B^0 lifetime, Δm_d is the $B^0\overline{B}^0$ mixing frequency, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 is incorrectly tagged as a $\overline{B}^0$ or vice versa. The tagging algorithm has six mutually exclusive tagging categories [3]. A non-zero value of the parameter C would indicate direct *CP* violation.

2 Analysis Method

Considering the K^0_S candidates reconstructed in $\pi^+\pi^-$, we reconstruct the signal candidates combining K^0_S and K^+K^-, η', π^0, $K^0_S K^0_S$, ρ^0, ω, or another K^0_S candidate. We also reconstruct the K^0_S candidates in $\pi^0\pi^0$, and they are combined with K^+K^-, η', or $K^0_S K^0_S$ (both in $\pi^+\pi^-$). Finally, we reconstruct the modes $B^0 \to K^+K^-K^0_L$ and $B^0 \to \eta' K^0_L$, where a K^0_L candidate is identified either as an unassociated cluster of energy in the EMC or as a cluster of hits in the IFR. The η' candidates are reconstructed in $\rho^0\gamma$ and in $\eta\pi^+\pi^-$, with η candidates in $\pi^+\pi^-\pi^0$ (not considered in the signal candidates with $K^0_S \to \pi^0\pi^0$ and K^0_L) and in $\gamma\gamma$.

We use the informations from the tracking system, the EMC and the DIRC to identify pions and kaons in the final state. Two kinematic variables are used to discriminate between signal decays and combinatorial background. The first is ΔE, the difference between the center-of-mass (CM) energy of the B candidate and the CM beam energy. The second is the beam-energy-substituted mass $m_{\rm ES} \equiv \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$, where the B candidate momentum $\mathbf{p}_B$ and the four-momentum of the initial $\Upsilon(4S)$ state $(E_0, \mathbf{p}_0)$ are defined in the laboratory frame. In the $\pi^0 K^0_S$ and $K^0_S K^0_S K^0_S$ analyses, these variables are replaced by the invariant mass of the reconstructed B meson, m_B, and the missing mass $m_{\rm miss} = |q_{e^+e^-} - \hat{q}_B|$, where $q_{e^+e^-}$ is the four-momentum of the e^+e^- system and $\hat{q}_B$ is the four-momentum of the B candidate after applying a B^0-mass constraint.

Background events arise primarily from random combinations of particles in continuum $e^+e^- \to q\overline{q}$ events ($q = u, d, s, c$). We reduce these with requirements on shape-event variables, like the angle $\theta_{\rm T}$ between the thrust axis of the B candidate in the $\Upsilon(4S)$ frame and that of the rest of the charged tracks and neutral calorimeter clusters in the event. In the fit we discriminate further against $q\overline{q}$ background with a Fisher discriminant $\mathcal{F}$ or a neural network (NN) which combines several variables that characterize the production dynamics and energy flow in the event [18]. We study the background from other B decays using Monte Carlo (MC) simulated events. We take care of this background adding specific components in the fit.

We obtain the *CP*-violation parameters and signal yields for each mode from extended maximum likelihood fits with the input observables ΔE, $m_{\rm ES}$, $\mathcal{F}$ or NN, Δt (all modes) as well as the resonance mass and decay angle ($\rho^0 K^0_S$ and ωK^0_S). In the case of modes with K^0_L the B mass kinematic constraint is necessary to determine the K^0_L momentum so that $m_{\rm ES}$ cannot be exploited in the fit. In the fits, the likelihood for a given event is the sum of the signal, continuum and the B-background likelihoods, weighed by their respective event yields.

In the $K^+K^-K^0$ analysis, we use an angular moment analysis to extract strengths of the partial waves in K^+K^- mass bins. In this approach we rely only on the assumption that the two lowest

Table 1: Preliminary fit results for each penguin mode. The second column gives $\beta_{\rm eff}$ or S, the third the result for the A_{CP} or C. The first errors given are statistical and the second systematic. See text for the description of ϕK^0 and $f_0(980)K^0$ results.

Mode	$\beta_{\rm eff}$	A_{CP}
$\boldsymbol{K^+K^-K^0}$		
	$0.361\pm0.079\pm0.037$	$-0.034\pm0.079\pm0.025$
ϕK^0		
	$0.06\pm0.16\pm0.05$	$-0.18\pm0.20\pm0.10$
$f_0(980)K^0$		
	$0.18\pm0.19\pm0.04$	$0.45\pm0.28\pm0.10$
Mode	S	C
$\boldsymbol{\eta' K^0}$		
	$0.55\pm0.11\pm0.02$	$-0.15\pm0.07\pm0.03$
$\boldsymbol{\pi^0 K^0_S}$		
	$0.33\pm0.26\pm0.04$	$0.20\pm0.16\pm0.03$
$\boldsymbol{K^0_S K^0_S K^0_S}$		
	$0.66\pm0.26\pm0.08$	$-0.14\pm0.22\pm0.05$
$\boldsymbol{\rho^0 K^0_S}$		
	$0.17\pm0.52\pm0.26$	$0.64\pm0.41\pm0.25$
$\boldsymbol{\omega K^0_S}$		
	$0.62^{+0.25}_{-0.30}\pm0.02$	$-0.43^{+0.25}_{-0.23}\pm0.03$
$\boldsymbol{K^0_S K^0_S}$		
	$-1.28^{+0.80}_{-0.73}{}^{+0.11}_{-0.16}$	$-0.40\pm0.41\pm0.06$

partial waves (S- and P-wave) are present, but make no other assumption on the decay model. Furthermore, for this mode we develop a novel technique based on a time-dependent Dalitz plot analysis, to take into account the variation of *CP* content and interference naturally in the fit. We use an isobar model where we include the resonances $f_0(980)$, $\phi(1020)$, $X_0(1550)$, and χ_{c0}. In addition to resonant decays, we include non-resonant amplitudes. We extract $\beta_{\rm eff}$ and $A_{CP} = -C$ from the asymmetries in amplitudes and phases between B^0 and $\overline{B}^0$ decays across the Dalitz plot.

3 Results

The fit results for the *CP* parameters are given in Table 1. In $K^+K^-K^0$ analysis, we find that the trigonometric reflection at $\pi/2 - \beta_{\rm eff}$ is disfavored at 4.6σ, which is the first such measurement in penguin decays. From the angular moment analysis we find the P-wave fraction to be 0.29 ± 0.03 averaged over the Dalitz plot, and 0.89 ± 0.01 over the ϕ resonance region ($1.0045 < m_{K^+K^-} < 1.0345$ GeV/c^2). We perform also a fit to low-K^+K^- mass region ($m_{K^+K^-} < 1.1$ GeV/c^2) in order to measure *CP*-asymmetry parameters for ϕK^0 and $f_0(980)K^0$ components. This is the first measurement of the *CP* parameters in $f_0(980)K^0$ with $f_0(980) \to K^+K^-$.

All measurements reported here are statistics limited. The main sources of systematic errors are the Dalitz plot model ($K^+K^-K^0$), the *CP* content of $B\overline{B}$ background, the reference shape modeling, the interference with other resonances ($\rho^0 K^0_S$), and the SVT alignment ($\pi^0 K^0_S$, $K^0_S K^0_S K^0_S$,

$K_S^0 K_S^0$).

The individual sin2β_{eff} results are in agreement with the charmonium value. The sin2β_{eff} for $\eta' K^0$ is inconsistent with zero by 4.9 standard deviations. The S value for $K_S^0 K_S^0$ is consistent with zero. None of the modes studied exhibits non-zero direct *CP* violation.

4 Conclusion

We have presented preliminary results on mixing-induced and direct *CP* violation for loop-dominated B decays. We have studied several modes, reconstructing several sub-decays for each mode in order to increase the statistics. We have improved the analyses using better techniche, like time-dependent Dalitz plot analysis.

All individual penguin modes are in agreement with the SM expectation. However, the sin2β_{eff} measurements are lower than the charmonium value so that their average appears to be rather low. With the increase of statistics, we are very close to measure the *CP* violation in the penguin modes with $b \to s$ transition.

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